

October 18, 2012

Prospects for PANDA in Charmonium and Charm Physics

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The prospects of the future PANDA experiment at FAIR in Darmstadt/Germany in the field of charmonium and charm spectroscopy are discussed.

PRESENTED AT

Charm2012
Honolulu, Hawaii, USA, May 14-17

1 The PANDA Experiment and Physics Program

The PANDA experiment [1] to be build at the future site FAIR (Facility for Antiproton and Ion Research) in Darmstadt in Germany is optimized for high precision hadron physics in the charmonium mass region. The experiment utilizes an antiproton beam with high precision and high luminosity as well as a versatile detector. The produced antiprotons at FAIR are stored and cooled in the HESR (High Energy Storage Ring) with a momentum resolution of up to 10^{-5} in the momentum range between 1.5 to 15 GeV/ c . The antiprotons can collide with the internal target of the PANDA experiment, providing a luminosity of up to $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The detector consists of a target spectrometer with a solenoid magnet surrounding the interaction region and a forward spectrometer with a dipole magnet. The detector covers almost 4π of the solid angle. Precise vertex reconstruction is achieved by a vertex detector in the target spectrometer. Charged particle tracking with high resolution, precise electromagnetic calorimetry over a wide energy range as well as muon identification are provided by both spectrometers. DIRC detectors in the target spectrometer complete the particle identification system.

The experimental setup allows to address many topics in hadron physics, including the study of QCD bound states, non-perturbative QCD dynamics, hadrons in nuclear matter, hyper-nuclear physics, electromagnetic processes as well as electroweak physics. The addressed topics are discussed in detail in [1]. In this contribution the prospects of PANDA in charmonium and open charm spectroscopy are highlighted.

2 Spectroscopy in the Charm Mass Region

2.1 Charmonium System

Charmonium spectroscopy has been proven a very powerful tool for the understanding of the strong interaction in the past decades. Due to the high mass of the charm quark, the $c\bar{c}$ system can be treated in non-relativistic potential models, where the potential is chosen to reproduce the properties of the strong interaction and the free parameters are obtained from comparison to data. While the gross features of the spectrum are reasonable described by these models, calculations in various theoretical frameworks are carried out to understand the finer features[2]. To distinguish between the various approaches, precise experimental data is required.

All eight predicted charmonium states below the open charm threshold have been identified experimentally[3]. Above the threshold only a few of the predicted states have been classified. On the other hand many states referred to as the X,Y, and Z states have been discovered recently in this mass region. The unexpected properties of some of these states make it difficult to interpret these as conventional charmonium

states and their nature is controversially discussed [4]. Resolving the situation above the threshold is an important task in spectroscopy.

2.2 Gluonic Excitations

For a complete understanding of the hadron spectrum it is important to take the coherent interaction of the gluons into account, which can manifest in the formation of a gluon tube between the constituent quarks. Excitations of this tube will add additional degrees of freedom to the hadronic bound state. This form of hadrons is referred to as hybrids, which will appear as supernumerary to the $q\bar{q}$ states expected from the naive quark model. In the simplest scenario the $c\bar{c}$ bound state is in an S -wave configuration and the flux tube in a 1^- color-magnetic or 1^+ color-electric excitation resulting in the lightest 8 hybrid states, where three states have exotic quantum numbers J^{PC} , which are forbidden for a $q\bar{q}$ system. Most predictions agree that the 1^{-+} state is the lightest charmonium hybrid with exotic quantum numbers having a mass of about $4300 \text{ MeV}/c^2$ [5]. Predicted decay modes for charmonium hybrids are $\chi_{c1}\pi^0\pi^0$, $J/\psi\pi^0\pi^0$, $J/\psi\omega$ and $D\bar{D}^*$. In the light quark sector the $\pi_1(1400)$ and $\pi_1(1600)$ with $J^{PC} = 1^{-+}$ are discussed as hybrids. Both are also observed in $\bar{p}p$ annihilation at rest with rates comparable to those of conventional mesons. So there is a large potential for PANDA to discover such states in the charmonium sector.

It is also expected that the self-interaction of gluons can form glueballs, bound states consisting of only gluons. Lattice QCD calculations predict the glueball ground state to be a scalar with a mass of about $1500 \text{ MeV}/c^2$ [6]. The $f_0(1500)$ observed in $\bar{p}p$ annihilation is discussed to be a glueball. Excited glueballs are predicted to fall into the mass range of the charmonium system. In particular the lightest states with exotic quantum numbers are predicted at $4100 \text{ MeV}/c^2$ (2^{+-}) and $4740 \text{ MeV}/c^2$ (0^{+-}). Since gluons do not distinguish between flavors, glueballs should couple to hadronic final states independently of their flavor (flavor blindness). Thus heavy glueballs should, like charmonia and hybrids, also decay into hidden charm states and D meson pairs.

2.3 Open Charm Mesons

Containing a heavy and a light quark, D mesons are very interesting objects for the understanding of QCD. In the heavy quark limit $m_c \rightarrow \infty$, the charm quark can be seen as a static color source. On the other hand, the light quark introduces chiral symmetry breaking and restoration. Until 2003 the spectrum of D_s mesons was regarded as well understood in potential model calculations[11]. At that time the two narrow states $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ have been discovered. The masses of these states are considerably lower than predicted. To explain this discrepancy a series of theoretical work was carried out in various frameworks[12]. Interpretations include conventional $c\bar{s}$ states, tetra-quark states and – for $D_{s0}^*(2317)^+$ – a DK molecule.

3 Prospects for PANDA

3.1 Mass and Width Scans

In antiproton-proton annihilation all states with non-exotic quantum numbers J^{PC} can be accessed directly in formation. This allows PANDA to carry out scan experiments, where the cross section of a resonance is measured as a function of the center of mass energy in fine steps. From the observed cross section one can measure the mass and width of the scanned resonance very precisely, since the measurement is not limited by the detector resolution. The uncertainties are rather given by the beam momentum, which is known very precisely. The method has been proven very successful by the Fermilab $\bar{p}p$ annihilation experiments E760 and E835. The E835 measurement [7] of the χ_{c1} mass and widths ($m = (3510.719 \pm 0.051 \pm 0.019) \text{ MeV}/c^2$, $\Gamma = (876 \pm 45 \pm 26) \text{ keV}$) are the most precise up to date.

Having direct access to all charmonium states with masses below $5 \text{ GeV}/c^2$ and performing measurements with highest precision will put the PANDA experiment in a unique position in the next decade. In particular the η_c and $\eta_c(2S)$ masses can be measured to precisely obtain the $1S$ and $2S$ hyper-fine mass splitting. Likewise the precise determination of the h_c mass and its position with respect to the spin-triplet χ_c states will provide more insight into the spin-dependence of the long-range potential. A detailed simulation for the measurement of the h_c reconstructed in its radiative decay to η_c , followed by $\eta_c \rightarrow \phi\phi$ and $\phi \rightarrow K^+K^-$ was performed and sufficient background rejection and efficiency is obtained to allow a scan with 10 scan points and 40 days of data taking[1].

Among the newly discovered states above the open charm threshold is the $X(3872)$, a narrow state ($\Gamma < 1.2 \text{ MeV}$) with $J^{PC} = 1^{++}$ or 2^{-+} decaying into $J/\psi\pi\pi$ and $D\bar{D}^*$ [3]. The mass of the state is $(3871.68 \pm 0.17) \text{ MeV}/c^2$. It is widely believed that the closeness of the $X(3872)$ to the $D\bar{D}^*$ mass threshold is related to its nature. It is suggested that the $X(3872)$ is a weakly bound $D\bar{D}^*$ molecule below or a virtual state above the threshold[8]. The current experimental uncertainties do not allow to distinguish between the two scenarios. It is also proposed, that the line shape of the $X(3872)$ in the $J/\psi\pi\pi$ and $D\bar{D}\pi^0$ decay modes might allow to distinguish between the two possibilities. A precise scan of the resonance in both decay modes at PANDA will improve the experimental situation on the $X(3872)$ dramatically[13].

3.2 Exotic Charmonium Hybrid

The lightest exotic charmonium hybrid is predicted to be a 1^{-+} state in the mass region of about $4300 \text{ MeV}/c^2$. Its width can be narrow and decays to open and hidden charm are expected. Two prime decay modes could be $\chi_{c1}\pi^0\pi^0$ and $D\bar{D}^*$. Any state with exotic J^{PC} can only be accessed in production with an associated recoil

system. In a detailed simulation study the production of the exotic hybrid state with a recoiling η has been investigated at a center-of-mass energy of $\sqrt{s} = 5.38 \text{ GeV}/c^2$. The hidden charm intermediate state is reconstructed from the $\chi_{c1} \rightarrow J/\psi \gamma$ and $J/\psi \rightarrow e^+e^-$ decays, leading to a final state with two leptons and seven photons. The open charm decay mode is reconstructed from the $D^* \rightarrow D\pi^0$ and $D \rightarrow K^+K^-\pi^0$ decay modes, leading to a final state with four charged kaons and eight photons. Reactions with only light hadrons have been proven to be suppressed sufficiently for $D\bar{D}$ and $D^*\bar{D}^*$ production. Other backgrounds are reactions with an event topology similar to that of the signal reaction like $\bar{p}p \rightarrow \chi_{c1}\pi\eta\eta$, $\chi_{c1}\pi^0\pi^0\pi^0\eta$, $J/\psi\pi^0\pi^0\pi^0\eta$, $D\bar{D}\pi^0$. Excellent calorimetry is required to suppress these backgrounds. From the study a signal to background ratio of better than 10 is expected, if the cross sections for these reactions do not exceed the signal cross section by more than an order of magnitude.

Since no assumptions are made on the particular nature of the produced state in the study, the results are valid for any narrow object of a mass of about $4300 \text{ MeV}/c^2$. In particular the investigated $D\bar{D}^*$ decay would be interesting for heavy glueball searches.

3.3 Charged Charmonium-like States

Among the new charmonium-like resonances are three charged states $Z(4430)^+$, $Z_1(4050)^+$ and $Z_2(4250)^+$, discovered by Belle in $B \rightarrow ZK$ decays. The $Z(4430)^+$ is observed in its decay into $\psi(2S)\pi^+$ and $Z_1(4050)^+$ and $Z_2(4250)^+$ in their decays into $\chi_{c1}\pi^+$ [9]. Since they decay into a charmonium state and carry electric charge, their minimal quark content must be $c\bar{c}u\bar{d}$ and thus they are definitely of exotic nature. Confirmation from another experiment is still missing. All three states have been searched for at Babar[10]. No evidence was reported, but the upper limits set by Babar do not strictly rule out Belle's measurements.

At PANDA these states can be studied in $\bar{p}p$ production, in a simplest scenario together with a recoiling π^- . A further option for PANDA is to study these states in formation on a deuterium target ($\bar{p}d \rightarrow Z^-p$) with a spectator proton.

3.4 Open Charm Spectroscopy

An important quantity possibly allowing to distinguish between the different theoretical explanations to the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ [12] is the decay width of these states. Currently the widths are constrained by upper limits of about 3 MeV due to the experimental resolution. This is not sufficient to distinguish between the different theoretical approaches and draw further conclusions about the internal structure of these states.

At PANDA the D_{sJ}^+ mesons, $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$, can be produced in $\bar{p}p$ annihilation with a recoiling D_s^- meson. The cross section for the process $\bar{p}p \rightarrow D_{sJ}D_s^-$ depends on the width of the D_{sJ}^+ . By measuring the cross section in dependence of the center-of-mass energy near the threshold in fine energy steps, the D_{sJ}^+ width can be extracted from the observed cross section. This method is expected to be sensitive down to widths of about 100 keV [1].

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